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Verification Of A Super Double-Heterogeneous Spherical Lattice Model For Equilibrium Fuel Cycle Analysis

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Introduction

Advanced High Temperature gas-cooled Reactors (HTR) currently being developed (GFR, VHTR - Very High Temperature gas-cooled Reactor, PBMR, and GT-MHR) are able to achieve a simplification of safety through reliance on innovative features and passive systems. One of the innovative features in these HTRs is reliance on ceramic-coated fuel particles to retain the fission products even under extreme accident conditions. The effect of the random fuel kernel distribution in the HTR is addressed through the use of the Dancoff correction factor in the resonance treatment. In addition, the Dancoff correction factor is a function of burnup and fuel kernel packing factor, which requires that the Dancoff correction factor be updated during Equilibrium Fuel Cycle (EqFC) analysis.

The double-heterogeneous MCNP model recently developed at the Idaho National Laboratory (INL) contains tens of thousands of cubic fuel kernel cells, which makes it very difficult to deplete the fuel, kernel by kernel (KbK), for the EqFC analysis. In addition, it is not possible to preserve the cubic size and packing factor in a spherical fuel pebble. To avoid these difficulties, a newly developed and validated HTR pebble-bed Kernel-by-Kernel spherical (KbK-sph) model, has been developed and verified in this study. The verified double-heterogeneous KbK-sph MCNP[1] model will be used for a genetic HTR EqFC analysis and important safety parameters validation.

HLM Lattice Model and Results

The Next Generation Nuclear Plant (NGNP)[2] pebble unit lattice was chosen as a reference case in this study. The NGNP pebble unit lattice consists of a graphite reflected, 8.0 wt% enriched, uranium pebble-bed system. NPNG fuel zone contains 13,271 discrete TRISO fuel kernels[4] (UO_2, OD = 0.05 cm, density = 10.7 g/cc). The pebble fuel zone has an OD = 5.0 cm (fuel C-matrix zone volume = 65.45 cm^3), graphite shell OD = 6.0 cm, and a pebble packing factor = 0.64. The kernel density = 13,271 / 65.45 = 202.8 kernels / cm^3.

The homogeneous lattice model (HLM) consists of fuel kernels in a graphite matrix zone, graphite and Si-C outer zone, and He filled gap zone (He filled volume ratio = 1 - 0.64). First, the homogenized pebble fuel zone x-y angle ($0° < \theta < 360°$) was divided into 30 shells as shown in Fig. 1. Then, the x-z cone angle ($\Delta\varphi$=7.96°) was selected to cut one of the 1/30 sliced sphere to 1/13.824 (13271 / 30 / 32 = 13.824) divided volume, such that each divided slice will contain 32 fuel kernels, which is the number of kernels in each divided slice of the Super KbK-sph lattice model. Note that 13.824 is not an integer-multiple of 2. Then, these three zones are bounded by two pairs of reflecting (θ, ϕ) boundaries, and an outer He gas filled white boundary as shown in the Fig. 1. There are 9 homogeneous fuel zone cases:

(1) One whole pebble,
(2) One slice of x-y angle ($0° < \theta < 360°$),
(3) Three slices of x-y angle ($0° < \theta < 360°$),
(4) Five slices of x-y angle ($0° < \theta < 360°$),
(5) Seven slices of x-y angle ($0° < \theta < 360°$),
(6) Nine slices of x-y angle ($0° < \theta < 360°$),
(7) 11 slices of x-y angle ($0° < \theta < 360°$),
(8) 13 slices of x-y angle ($0° < \theta < 360°$), and
(9) 15 slices of x-y angle ($0° < \theta < 360°$).

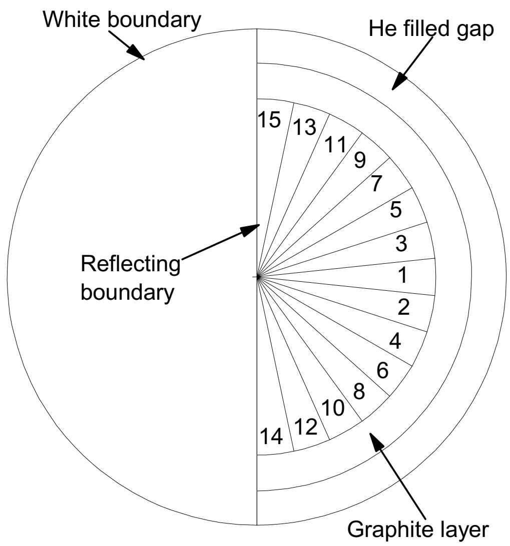

Figure 1. X-Y cross-sectional view of a double-heterogeneous triangular fuel unit lattice model with fuel kernels.

The MCNP-calculated K_∞ of the single-heterogeneity of the HLM, i.e. without fuel kernel self-shielding by smearing the fuel kernels in the fuel zone, of these nine cases are 1.401675±0.0006, 1.400787±0.0006, 1.399847±0.0007, 1.399738±0.0007, 1.402251±0.0007, 1.400266±0.0007, 1.400951±0.0007, 1.399698±0.0006, 14.00162±0.0006, respectively.

For each case, the MCNP KCODE mode (with PVM = 4 tasks, 80 cycles with 5000 source neutrons) calculation run requires 60 minutes of DELL-650 XEON-2-CPU 3.06 GHz workstation computer time to achieve a one standard deviation (1σ) less than 0.06%.These results indicate that a whole pebble lattice can be represented by any number of slices of pebble in the HLM. As a result, the KbK-sph model, which contains only 32 fuel kernels in each slice with reflecting boundaries, can adequately represent the randomly distributed 13,271 fuel kernels.

Super KbK-sph Lattice Model and Result

To build a super double-heterogeneous MCNP Kernel-by-Kernel particle Fuel with a spherical lattice (KbK-sph) model from HLM with 10 fuel pebble slices, first, each fuel zone slice volume is 65.45/30.0 /13.824 = 0.1578 cm^3, which will contain exactly 32 fuel kernels. Then, the fuel C-matrix is spherically divided into 32 equal-volume shells, such that, each sub-shell contains one fuel kernel to maintain a constant kernel density, as shown in the Fig. 2. To make 32 kernels distribute more random-yet-orderly, the fuel kernel was allocated by the cone-shaped spiral curve around the slice median-axis in each of 32 subdivided radial shells.

The MCNP-calculated K_∞ of the single-heterogeneity of the HLM, i.e. without fuel kernel self-shielding by smearing the fuel kernels and pebble and the double-heterogeneity KbK-sph model are 1.4042±0.0006 and 1.5212±0.0005, respectively, which represents a ΔK = 0.1170. The verification and validation (V&V) of the HTR one slice lattice KbK-sph model was presented in Ref. 3 and 4.

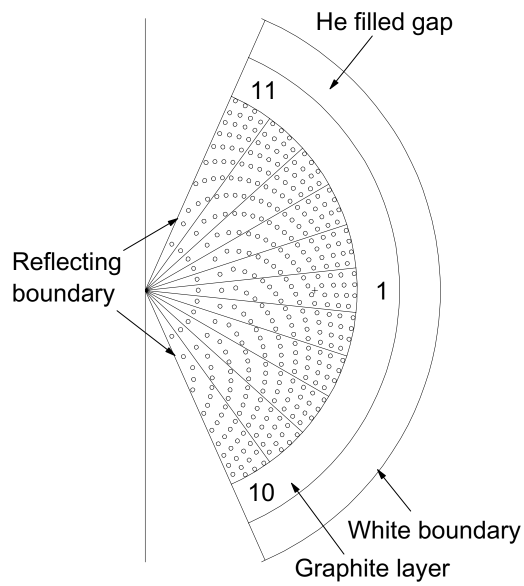

Figure 2. X-Y cross-sectional view of a super double-heterogeneous KbK lattice model with a random-yet-orderly fuel kernel distribution

The NGNP (600 MWt) design can achieve a continuous on power refueling cycle with pebble total residence time of about 660 days. Let us assume the number of passes per pebble is 11 (this number can be varied to a specific design need) and 60 days per one fuel shuffling interval. The EqFC can be achieved by the following shuffling scheme. At the beginning of the 2nd 60 effective full power days (EFPD), slice one will be reset to fresh fuel kernels, while the rest of the fuel slices are kept the same for the new 60 EFPD cycle. At the beginning of 3rd 60 EFPD cycle, the 2nd fuel slice will be reset to fresh fuel kernels. The beginning of EqFC state can be achieved at the beginning of the 11^{th} cycle by resetting the 10^{th} fuel slice to fresh fuel kernels. Then, at the end of the 11^{th} cycle, the 11^{th} slice will achieve the discharge burnup with 660 EFPD.

Conclusions

In this study, we show that HLM and KbK-sph models with any number of slices of pebble can adequately represent the whole pebble lattice characteristics. The double-heterogeneous KbK-sph lattice model used in this study can handle the complex spectral transitions at the boundaries between the kernels in a straightforward fashion and treat the entire lattice at once.

A new verified depletion tool MCWO[5], (MCNP coupled With ORIGEN-2[6]) will be used to analyze the KbK-sph and HLM EqFC burnup characteristics. The MCWO-calculated results, such as, K_∞ , Xe-worth, and important burnup characteristics versus EFPD are compared and discussed in the further study.

The KbK-sph and HLM and MCWO can be used to perform the neutronics analysis for particle fuel testing in the Advanced Test Reactor (ATR). The KbK-sph and HLM can also be used in a wide variety of other applications, including advanced HTR (both fast and thermal neutron flux Gen-IV reactors) fuel cycle performance analysis, long life minor actinide transmutation, strong absorber depletion analysis, and HTR fuel and reactor materials test assembly design.

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